

High Order Wavefront Correction for High Contrast Imaging

**John Trauger, JPL
Mark Ealey, Xinetics
Roger Bagwell, Xinetics
Dwight Moody, JPL
Yekta Gursel, JPL
Brian Gordon, JPL**

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Abstract

We describe the science rationale and technical requirements for high contrast imaging in space astronomy, and review recent developments in an enabling deformable mirror technology now in progress at JPL and Xinetics.

The next decade in space astronomy will bring together lightweight optical telescope architectures and active mirror technologies for wavefront correction. NGST is an early example of this concept, a telescope designed from the outset with articulated mirror segments that will be aligned and actively corrected on orbit.

Precision deformable mirror technology has advanced significantly. We describe a modular deformable mirror design that has demonstrated angstrom RMS surface accuracies and that is scalable to thousands of active elements. Such mirrors could facilitate the correction of high order surface figure errors that are typically seen in large telescope mirrors, improving spatial resolution and contrast beyond current capabilities for large optical systems on the ground and in space.

In particular, an active coronagraphic space telescope will enable imaging and spectroscopy of stellar companion objects that are fainter than the primary by factors of order 10^{-9} or more at separations of arcseconds or less. Such an observatory will facilitate pioneering explorations of hundreds of nearby planetary systems, including direct detection and spectroscopy of planets, Kuiper-analogue debris disks, brown dwarf companions, and young stellar objects.

Applications in space astronomy

- High quality imaging with lower precision optics
 - Wide field diffraction-limited visible imaging with a telescope – such as NGST – optimized for the infrared
 - Provides telescope design trades, i.e. mass and complexity of primary mirror support structure versus on-orbit wavefront correction
- Coronagraphic imaging (camera with occulting spot and Lyot stop)
 - Potential science includes discovery and characterization of stellar companions and debris structures that would otherwise be lost in the glare of a central bright star.
 - Coronagraph removes diffracted light from the image, but cannot control light scattered by surface figure errors on the telescope optics.
 - Surface figure must be corrected to very high accuracy at spatial mid-frequencies.

Wavefront correction of lightweight telescope mirrors

- Wavefront corrections can be done with a deformable mirror at an intermediate pupil plane
- Active wavefront correction for space astronomy is different from adaptive correction of atmospheric seeing on the ground.
 - Smaller magnitude corrections with a premium on wavefront accuracy
 - Operational efficiency requires very high stability / very low bandwidth

Potential advantage with deformable mirrors

- Can reduce surface figure errors beyond the state-of-the-art for large optics
- Provides a method to maintain high wavefront quality in system trades against lightweighting and complexity of the primary mirror.
- Enables high contrast imaging and dark hole coronagraphy
- DMs can be used to correct the on-orbit optical figure with information available on-orbit, guided by feedback from iterative phase retrieval from a star image.

“But at what cost...”

- May introduce wavefront errors at spatial frequencies beyond the pitch of the DM actuators, depending on the surface finish and actuator influence function of the DM.
- Creates new requirements on optical system stability, including:
 - Introduces DM temperature control requirements (0.1 to 0.01 °C with PMN electrostrictive actuators)
 - Optical tolerance for pupil image shear and geometric distortion are of order $\delta/D = [2\pi nq]^{-1}$, for a system in which n^{th} -order mirror surface ripple is reduced by a factor q at the DM
- A large number of actuators is needed to clear a large and deep coronagraphic dark hole.
- Added complexity and risk to optical system, electronics, and calibration.

Electrostrictive PMN Actuator Technology

- PMN technology is now widely used in adaptive optical systems, and has been qualified for space applications (WFPC2).
- This is an extension of current adaptive optics technology to smaller and more precise deformations and higher actuator densities.
 - Xinetics development – 1 mm pitch, 0.4 μm stroke, in 21×21 mm (441 actuators) modules that can be mated together on all four sides.
- Open loop application are possible due to low levels of PMN actuator creep.

Deformable Mirror Test Program

- Measurements are made with a thermal/vibration/vacuum-isolated Michelson interferometer
- Surface figure error is measured to 1 Angstrom rms accuracy over continuous periods of a month or more
- Actuator influence profile is sampled in an 8×8 grid across each 1mm square actuator domain.
- Surface figure phase maps are extracted from a stack of 81 interferograms.

Deformable Mirror Performance

- Surface influence profile confirms design predictions.
- Patterns are stable and repeatable to the measurement accuracy

Multiplexed Driver Electronics

- Low-leakage capacitive nature of actuators is consistent with multiplexed driver approach.
- Multiplexed driver gracefully handles the large numbers of actuators.
- Multiplexer approach provides open loop “set-and-forget” operation.
- Individual actuators are electrically contacted with a single flexible circuit per module

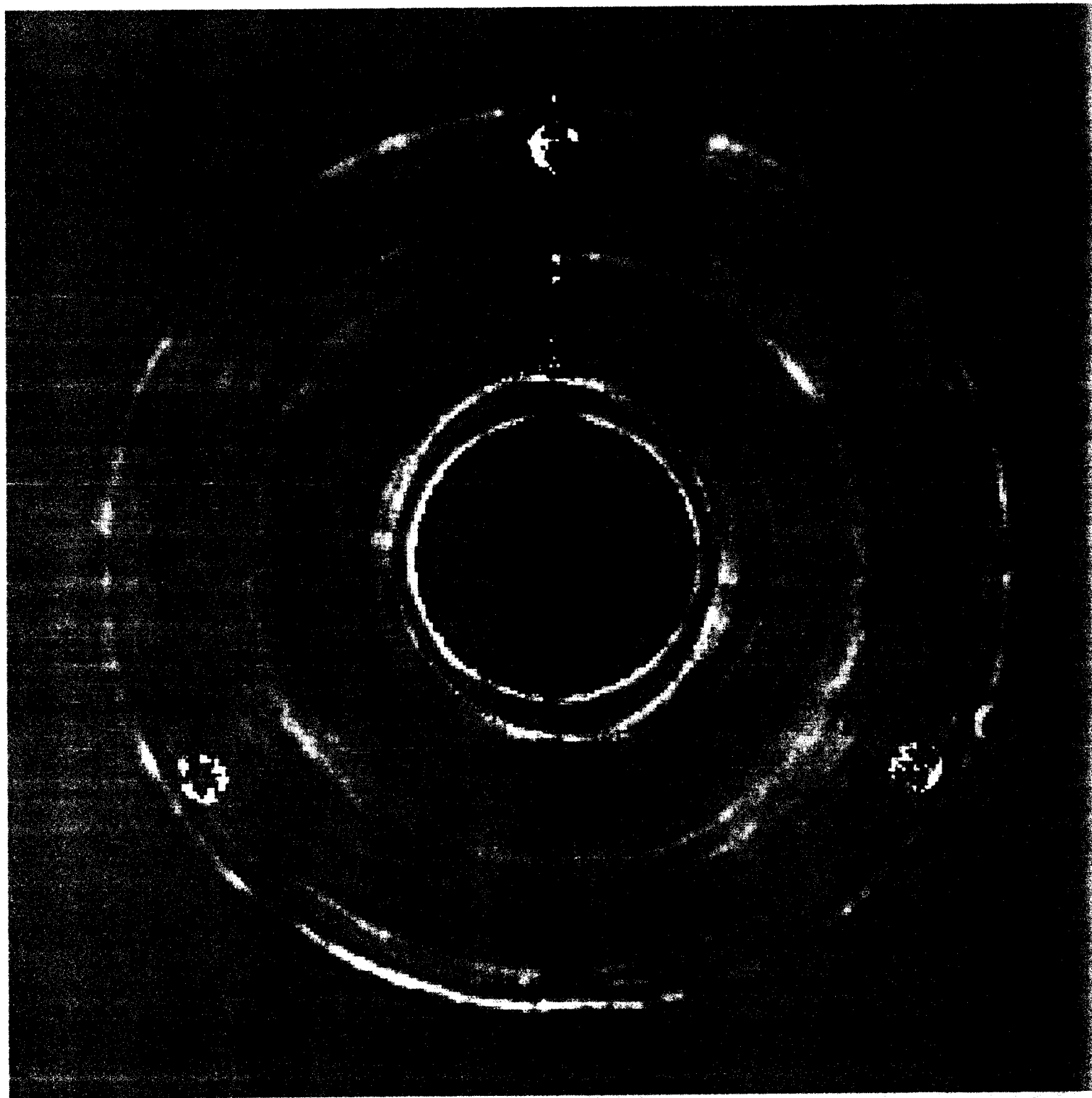
Ongoing work

- Demonstration of larger DM assemblies
 - 42 mm diameter DM with 1385 actuators in a 2×2 module assembly with a continuous facesheet has been fabricated
 - 63 mm diameter DM with 3117 actuators in a 3×3 module assembly with a continuous facesheet and SiC strongback structure will be fabricated this year
- Demonstration of precision wavefront correction and high contrast coronagraph imaging in the laboratory ongoing in JPL laboratories

Summary

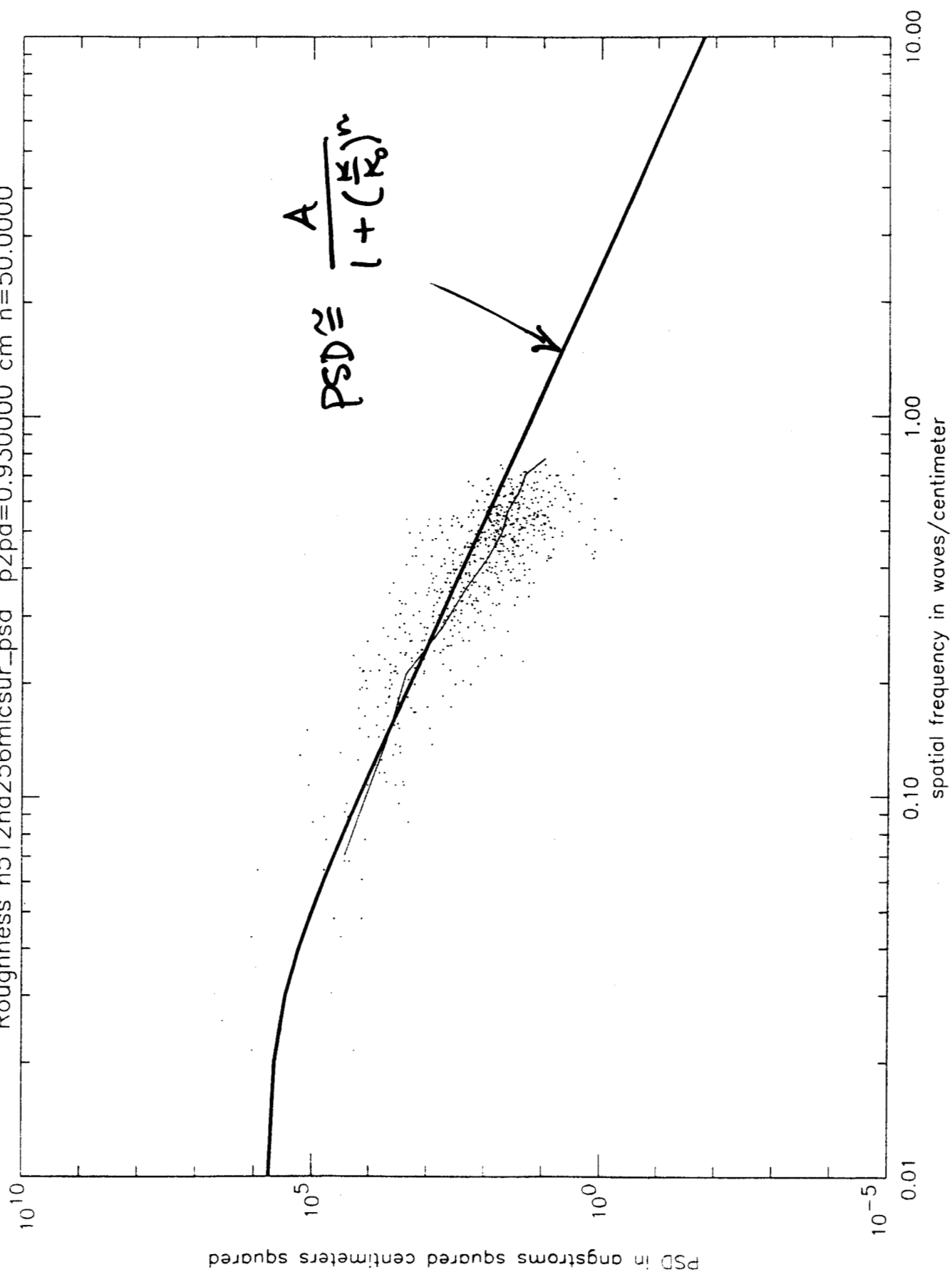
- A method to reduce wavefront errors produced by large optical mirror elements in space.
- We contemplate applications that –
 - (1) Correct surface figure errors due to a single large optical element (such as the primary mirror) for wide fields of view, or
 - (2) Correct wavefront errors for an entire optical system when one point in the field of view is most critical (such as a coronagraph).

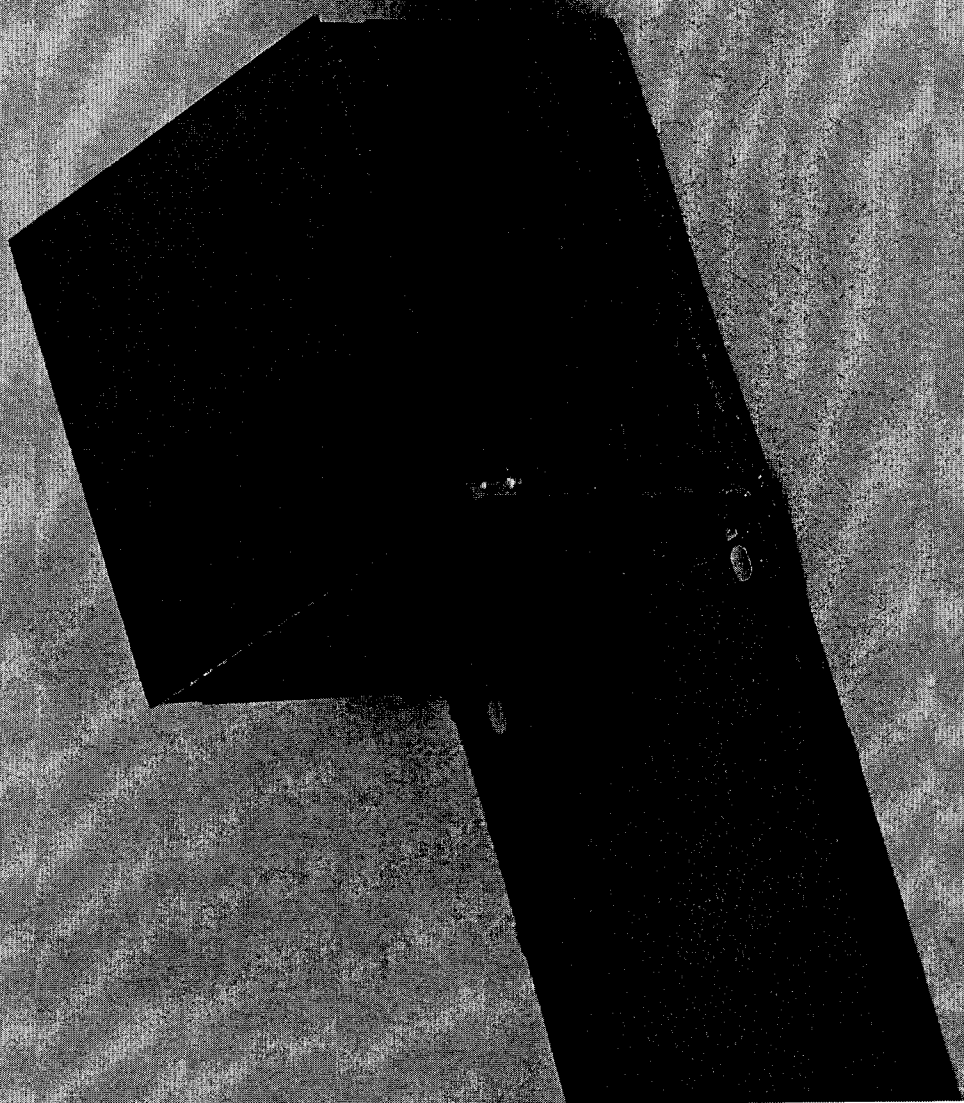
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HST (Krist & Burrows 1995)

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Surface displacement (waves at 633nm)

